TESTING FOR X-RAY PERIODICITIES IN SEYFERT GALAXIES

FINAL TECHNICAL REPORT FOR NAG 5-9094

ABSTRACT

The Deep Survey instrument on the *Extreme Ultraviolet Explorer* obtained long, continuous light-curves of 10 Seyfert galaxies with durations of 5–33 days each. We present a uniform reduction of these data, which account for a total of 209 days of observation. Several of the light curves are uniquely suited to a search for periodicity or QPOs in the range of hours to days that might be expected from dynamical effects in the inner accretion disks around $\sim 10^8\,M_\odot$ black holes. Power spectra show features in three of the longest observations that could be transient periods: 0.9 days in RX J0437.4–4711, 2.1 days in Ton S180, and 5.8 days in 1H 0419–577. These period values seem to be unrelated to the length of the observations, which are similar in the three cases, but they do roughly scale as the luminosity of the objects, which would be expected in a dynamical scenario if the black hole masses also scale with luminosity. The significance of these periods will be evaluated in a future publication by using the method of Timmer & König (1995), which properly takes into account the red-noise properties of AGN light curves.

1. Introduction

Some Seyfert galaxies have shown transient or quasiperiodic oscillations with periods of order 1 day. The first such evidence was obtained in a 20 day *EUVE* observation of the Seyfert galaxy RX J0437.4–4711 (Halpern & Marshall 1996), where a possible signal at a period of 0.906 ± 0.018 days was detected. If attributed to relativistic beaming or other projection effects of orbiting structures at a radius of $6\,GM/c^2$, a 0.9 day period requires a black hole mass of $1.7 \times 10^8\,M_\odot$. Since this is the time scale on which one might expect find periods or QPOs corresponding to orbital motion in the inner accretion disk around black holes in AGNs, it is reasonable to hypothesize that such signals may be common, while the dearth of continuous X-ray observations of sufficient duration has prevented them from being recognized until now.

X-ray observations of AGNs that would be long enough to convincingly detect such periodic signals are rare. Although several long light curves of quasars near the ecliptic poles were obtained by the *ROSAT* All-Sky Survey, those objects did not vary during the monitoring period, e.g., Kolman et al. (1993); Treves et al. (1995). The *EXOSAT* long-look observations of Seyfert galaxies, e.g., Green, MsHardy, & Lehto (1993), provided continuous light curves but the longest was 3 days in duration so it did not sample variability on time scales longer than 1 day. There have been several analyses of possible QPO features with periods of 1 hr or less in the *EXOSAT* observations of NGC 4051 and NGC 5548 (Bao & Østgaard 1994; Papadakis & Lawrence 1993, 1995), although the NGC 5548 claim has not withstood critical analysis (Tagliaferri et al. 1996). A continuous 4 day long observation of NGC 3516 with *RXTE* did not detect any periodicity (Edelson & Nandra 1998). The many "reverberation-mapping" campaigns have been longer in duration, but most were not sensitive to X-ray variability on time scales of hours to a few days. One exception is the month-long observation of NGC 7469 (Nandra et al. 1998). which did not, however, reveal any short-term periodicity. A possible indication of periodicity was obtained in a five-day *ASCA* observation of the Seyfert galaxy *IRAS* 18325–5926. A signal at 16 hr was seen in those data (Iwasawa et al. 1998). Lee et al. (2000) pointed to a possible 33 hr period in an 8 day observation of MCG–6–30–15 with *RXTE*. Boller et al. (2001) claimed that an 8 hr observation of Mkn 766 by *XMM-Newton* shows a period of 4200 s, although its significance according to the analysis of Benlloch et al. (2001) is not very high.

2. EUVE Observations of Seyfert Galaxies

The *EUVE* Deep Survey/Spectrometer (DS/S) telescope with Lexan filter was used for most of the pointed observations in the Guest Observer phase of the mission, from 1993 January through 2001 January. Although the DS Lexan band is sensitive in the range 67–178 Å, photons are detected from extragalactic sources only at the short wavelength end because of the steep increase in interstellar absorption as a function of wavelength. For example Halpern, Martin, & Marshall (1996) shows the effective distribution of detected counts in the DS for a range of power-law sources. Since nearly all of the detected flux is in the range 70–100 Å (0.12–0.18 keV), we refer to this band, according to convention, as soft X-rays.

It might not be well known that the *EUVE* Deep Survey imager (DS) made more long, continuous X-ray observations of Seyfert galaxies than any other X-ray satellite. *EUVE* made 20, nearly continuous observations (interrupted only by Earth occultation) of 10 Seyfert galaxies including the quasar 3C 273. The duration of these pointings ranged from 3 to 33 days. A log of the observations is given in Table 1. Together, these account for some of their detectability with *EUVE*, a difficult prospect which is enhanced by small Galactic and intrinsic column density. Also, Narrow-line Seyfert 1 Galaxys (NLS1s) are heavily represented because they are typically strong, soft X-ray sources with steep X-ray spectra (Leighly 1999b).

Many of these data sets have been published, at least in part, by the authors listed in the notes to Table 1. Most of these papers, however, were not concerned with power-spectrum analysis or periodicity. Several presented spectra of the Seyferts from the *EUVE* short-wavelength spectrometer, a heroic effort which, unfortunately, yields results that only a mother could love. However, the corresponding long DS light curves, which are of a quality ranging from mediocre to excellent, deserve a separate and comprehensive analysis. When such a light curve is binned into one point per satellite orbit, as Figures 1–4, it constitutes a uniformly sampled time series for which ordinary power spectrum analysis can be applied to search for features from 3 hours to several days.

3. Testing for Periodicity

It important in this business to explain what is meant by "periodicity". Since AGN power spectra are often dominated by red noise, it is difficult if not impossible to define a statistical test for periodicity, since such a feature is superposed on a continuum of power that is itself poorly characterized. Many calculations of statistical significance in the AGN literature are grossly wrong, since they are tests against the hypothesis of white noise, or worse, a constant source. Similarly, it will never be possible to establish a period in a Seyfert galaxy by marking off two or three peaks in a light curve, and calling their separation "the period". Accretion-powered sources flicker; the dominant feature of flickering is often an apparent variation of two or three "cycles" over the span of the observation. Perhaps the most rigorous analysis is that of Timmer & König (1995), who take into account both the Fourier phases and amplitudes in simulating power spectra from flickering or random-walk light curves. These are like AGN power-spectra, which typically follow the form $f^{-\beta}$ where β is in the range 1–2. We will apply this analysis in a future publication that rigorously evaluates the significance of peaks in the power spectrum.

In the meantime, we will use simplified criterea to designate interesting candidate periods. Most important, we require that there be a narrow peak or a QPO in the power spectrum that *i*) is clearly separated from the low-frequency noise, and *ii*) stands out high above the surrounding points. It is our opinion that the candidates reported here come close to meeting these criteria for significance, but they are not secure enough, if only because the signal is not always present throughout the entire observation. However, theory accommodates or even favors *transient* periods in Seyfert galaxies, since orbiting hot spots or other asymmetric structures in an accretion disk *should* have finite lifetimes due to Keplerian shear. They just need to be confirmed by repeat occurrences. A third requirement is that the number of cycles detected should be large. One would like to see at least 10 cycles of variation to prove the existence of a period; 20 cycles would be fabulous. These requirements (many cycles, allowing for transience) lead to an ideal observing time of 1 month to search for periodicity of order 1–2 days. Most of the light curves in Figures 1–4 show variations of order unity on 1–2 day time scales.

There are no technical problems that prevent the search for periodicities of order 1 day with *EUVE*. Most of the targets were well detected, and in most cases their variability amplitudes are larger than the counting statistics, which in turn are larger than background and systematic effects. The periods that we are searching for would constitute a major feature of the light curves, not a subtle secondary effect. We always take special care with dead-time and Primbsch corrections (loss of photons when the count rate is high because of designed telemetry sharing between the instruments on *EUVE*). These losses are usually due to high background radiation rates that are experienced in the vicinity of the South Atlantic Anomaly (SAA). Most notably, our published results are not contaminated by a periodic signal at 0.98 days that might have been generated by passages through the SAA, even though there is a strong modulation in the dead-time at this period. We can easily recognize and eliminate such an effect when it occurs. The key point is that the intrinsic variability amplitude of these sources is large and reliable, which we have verified though analyses of additional sources in the fields of these targets which are either constant, or show uncorrelated variability (Halpern & Marshall 1996; Halpern, Martin, & Marshall 1996; Halpern et al. 1998). We know of no instrumental or terrestrial effects that could be responsible for the candidate periods detected here.

4. Notes on Individual Objects

4.1. NGC 4051

NGC 4051 was the first Seyfert galaxy for which variability on time scales as short as 150 s was seen (Marshall et al. 1983). It has the lowest luminosity of the EUVE sample here, and it is probably not a coincidence that it exhibits the most rapid and large amplitude variability, in addition to extended low states in which the variability is reduced (Uttley et al. 1999). Its EUV flux was well correlated with simultaneous X-ray variations as observed by *RXTE*, with no measurable time lag, which in the Comptonization model for the hard X-rays implies that the Componizing region is smaller than $20\,R_{\rm Sch}$ for $M_{\rm BH} > 10^6\,M_\odot$ (Uttley et al. 2000). It is the one object that varies too rapidly to be adequately sampled once per *EUVE* orbit, so we do not attempt a power-spectrum analysis.

4.2. NGC 4515

Although NGC 4151 is one of the brightest Seyfert 1 galaxies in optical and X-ray, it is also highly absorbed at soft X-ray energies, so it is not surprising that it was a very weak EUV source.

4.3. NGC 5548

The observation of NGC 5548 in 1998 June was conducted simultaneously with *ASCA* and *RXTE* Chiang et al. (2000). These authors noted that the variations in the DS light curve actually seem to *lead* similar modulation at harder X-ray energies by 10–30 ks. They suggested that the EUV emission is indicative of the the fundamental variability, and that the optical through EUV portion of the spectrum provides the seed photons for the production of hard X-rays via thermal Comptonization.

4.4. RX J0437.4–4711

RX J0437.4–4711 is an ordinary Seyfert 1 galaxy that was detected serendipitously in a 20 day *EUVE* observation of the millisecond pulsar PSR J0437–4715, which lies only $4'$ away. The small Galactic column in this direction enhances the detectability of both objects. Results on the pulsar were published by Halpern, Martin, & Marshall (1996), and the Seyfert galaxy by Halpern & Marshall (1996). The power spectrum of 5(a) appeared in the latter paper, in which a possible period at 0.906 d was noted. The structure that is responsible this signal in RX J0437.4–4711 is evident in its light curve in Figure 3, especially in the second half of the observation. At least 11 cycles are present during the second half of the observation. Here, we note that the possible 0.906 d period is enhanced in the power spectrum if only the second half of the observation is used (Figure 5(b)).

4.5. Ton S180

Ton S180 is a NLS1 galaxy. Leighly (1999a) showed that NLS1s are more variable than ordinary Seyfert galaxies of similar X-ray luminosity, and the *EUVE* light curves of Ton S180 (and Mrk 478, another NLS1) seem to bear this out. The 33 day observation of Ton S180 in 1999 was the only one that suffered significantly from the effects of dead-time and Primbsching due to high background. However, the symptom of this is easily recognized and eliminated. When the background is high and the correction factor is $\gtrsim 2$, the correction becomes inaccurate, and one or two orbits per day are clearly discrepant from the others. These bad points produce a signal in the power spectrum at 0.98 days (and its harmonics), which is the period with which the SAA on the rotating Earth passes through the slowly regressing satellite orbit. When the bad points are excised, the 0.98 day signal in the power spectrum disappears. Figure 3 shows the light curve cleaned of bad points.

The power spectrum of the cleaned 1999 observation of Ton S180 (Figure 6) shows several possible periods, the strongest being at a period of 2.08 days. It is important to note that because the observation is so long, this period is not consistent with a sub-harmonic of the 0.98 day SAA period, as it is well resolved from it. Furthermore, the 2.08 day period is much stronger than any weak residual at 0.98 days (1.18×10^{-5} Hz) which is undetectable in the power spectrum. Weaker peaks in Figure 6 are present at 2.81 days and 1.32 days, again, with no known instrumental effect that could be responsible.

4.6. 1H 0419–577

The *EUVE* observation of 1H 0419–577 was the second longest in this compilation, 25 days. Its power spectrum, shown in Figure 7, has a peak at 5.8 days. Interestingly, 1H 0419–577 does not appear to suffer from as much red noise that dominates RX J0437.4–4711, Ton S180, and other Seyfert galaxies at low frequencies, thus the feature at 5.8 days is more prominent. It is not clear what is responsible for this qualitatively different behavior, or indeed if it is a permanent characteristic of the source. This light curve of 1H 0419–577 was published without any analysis in a paper about the serendipitous discovery of an new AM Her star only $4'$ from the Seyfert galaxy in this *EUVE* observation (Halpern et al. 1998). The latter paper illustrated that *EUVE* can reliably discover periods. In the case of the AM Her star, the period of 85.821 minutes was unambiguous despite its proximity to the satellite orbit period because the observation was so long. This may be the only *EUVE* observation in which two new periods were discovered.

5. Theoretical Implications

One notable pattern in the candidate periods detected here in three objects is apparent from their ordering as a function of redshift and luminosity. The flux of Ton S180 is approximately twice that of RX J0437.4–4711, and its redshift is slightly higher. Thus, the luminosity of Ton S180 is about 2.5 times that of RX J0437.4–4711. If the characteristic time scale is proportional to the mass of the black hole, which in turn is proportional to the luminosity, then one might expect the period of Ton S180 to be about 2.5 times that of RX J0437.4–4711, not far from the "observed" factor of 2.3. Since the fluxes detected by *EUVE* for RX J0437.4–4711 and 1H 0419–577 are approximately the same, their luminosities scale as z^2. Then one might expect the period of 1H 0419–577 to be about 4 times that of RX J0437.4–4711, not far from the "observed" factor of 6.

One of the surprising results that is apparent in the *EUVE* data is the large amplitude and rapid variability of some of the Seyfert light curves. Although it is generally true that variability amplitude in AGNs increases with increasing energy, it is now clear that EUV variability is as dramatic as any detected at higher energies. Therefore, it is of fundamental importance to measure variability in the EUV because of the likelihood that this component contains the bulk of the emission from the inner accretion disk, and most of the bolometric luminosity as well. This is certainly true in the case of RX J0437.4–4711. Because of its steep power-law spectrum of $\Gamma = 2.2 - 2.6$ as measured by *ROSAT* and *ASCA* (Halpern & Marshall 1996; Wang et al. 1998), the soft X-ray variability of RX J0437.4–4711 cannot be attributed to reprocessing of harder X-rays. The hard X-ray flux is less than that of the variable soft X-ray component. The same is true of two additional objects of this analysis, Ton S180 and Mrk 478. Thus, we are probably viewing with *EUVE* the intrinsic variability of the innermost part of the accretion disk, the primary energy source.

As hypothesized by Green, MsHardy, & Lehto (1993) for the *EXOSAT* sample, the absence of a substantial electron-scattering corona, which would otherwise smooth out the intrinsic variations, may be what allows us to see large amplitude variability in the soft spectrum EUV sources. In this picture, all Seyferts are intrinsically variable in the EUV. Those with flat X-ray spectra are the ones which possess the Comptonizing layer which is needed to produce the hard X-ray reflection component, and which also diminishes variability if present. But that is just one theory. We will be able to test it with these *EUVE* observations by correlating power-spectrum slope with X-ray spectral index, using a wider variety of objects than were observed by *EXOSAT*.

Theory is in fact quite challenged to produce the large-amplitude EUV variability that we observe. Because of the energetics argument presented above, one cannot beg the question of the origin of variability, as is often done, by appealing to reprocessing of harder X-rays.

The EUV is where we must address the fundamental question of why AGNs vary to begin with, and it would be helpful if we had a characteristic time scale and amplitude to work with. For example, the most promising "diskoseismic" theory of Nowak et al. (1997) predicts that radial g-modes will be trapped at the inner edge of a relativistic accretion disk, and that the observationally relevant frequency is $f = 714\ (M_\odot/M)\ F(a)$ Hz where $F(a)$ ranges from 1 to 3.44 as the dimensionless black-hole angular momentum parameter a ranges from 0 to 0.998. For a $10^8\,M_\odot$ black hole, the predicted period of oscillation ranges from 1.62 days for a Schwarzschild black hole to 0.47 days for a maximal Kerr black hole. This theory of accretion disk oscillations (Nowak & Lehr 1998), which has been applied to Galactic black-hole binaries, is capable of generating the appropriate *periods* of a few hours to days in AGNs, but it cannot account for *amplitudes* of more than a few percent. Thus, while they have some trouble in accounting for the variability of Galactic microquasars, accretion disk oscillations are even further removed from explaining the X-ray variability observed in Seyfert galaxies.

Like Ton S180 and Mrk 478 above, some of the most dramatically variable X-ray sources are NLS1s. These are by now well known for having steeper X-ray spectra than ordinary, broad-line Seyferts. Thus, they are ubiquitous in soft X-ray selected samples such as those of *ROSAT*. In *ROSAT* studies of selected NLS1s, Boller et al. (1997) and Brandt et al. (1999) hypothesized that relativistic beaming by orbiting asymmetries in the inner accretion disk must be partly responsible for their variability, which sometimes implies an efficiency greater than that possible for an isotropically emitting accreting source. If so, there should be at least some evidence for periodicity in their light curves if the emitting structures retain their coherence for several orbits. It is that sort of quasiperiodic signal that we are looking for in these long *EUVE* light curves. However, we are still far from developing a physical theory for what creates such structures. It thus appears that theory will continue to lag behind observation in this field until and unless some pattern to the observations emerges.

6. Conclusions

The foundation of the supermassive black hole model for AGNs rests squarely on their rapid X-ray variability, which establishes the compact nature of these luminous objects beyond a reasonable doubt. Although AGN variability has been exploited for various purposes, we have barely begun to address the question of *why* AGNs vary. The numerous "reverberation mapping" campaigns have not, as a by-product, shed much light on this issue. Simultaneous X-ray, UV, and EUV monitoring has cast a dark shadow over the whole enterprise, because it has become apparent that there is no simple relation among the light curves in the various bands, e.g., in the study of NGC 7469 by Nandra et al. (1998). In NGC 5548, there is some evidence that the underlying variability process is displayed in the EUV (Chiang et al. 2000), and this might be true generally for Seyferts in which the peak of the spectral energy distribution is in the EUV. but we still don't know how to interpret that variability. A fundamental obstacle to understanding is the apparent lack of a characteristic time scale, a period or quasiperiod which could be interpreted in terms of a dynamical or other time scale related to the size of the putative inner accretion disk and the mass of the black hole. It is difficult to interpret the aperiodic variability (flickering) which is characteristic of all accretion-powered objects, including AGNs. But if X-ray periods or quasiperiods could be found in just a few AGNs, they would provide a quantitative reference point for theory, just as QPOs in Galactic X-ray transients do for stellar-mass black holes. The lack of any confirmed X-ray periods in AGNs might be taken as evidence that they don't exist. On the other hand, the tentative detections reported here hint that we may not have observed sufficiently on the required time scales. All three *EUVE* observations that are 20 days or more in length show some indication of periodic behavior. Evidence is mounting that the possibility of studying periodic phenomena in Seyfert galaxies should be considered seriously.

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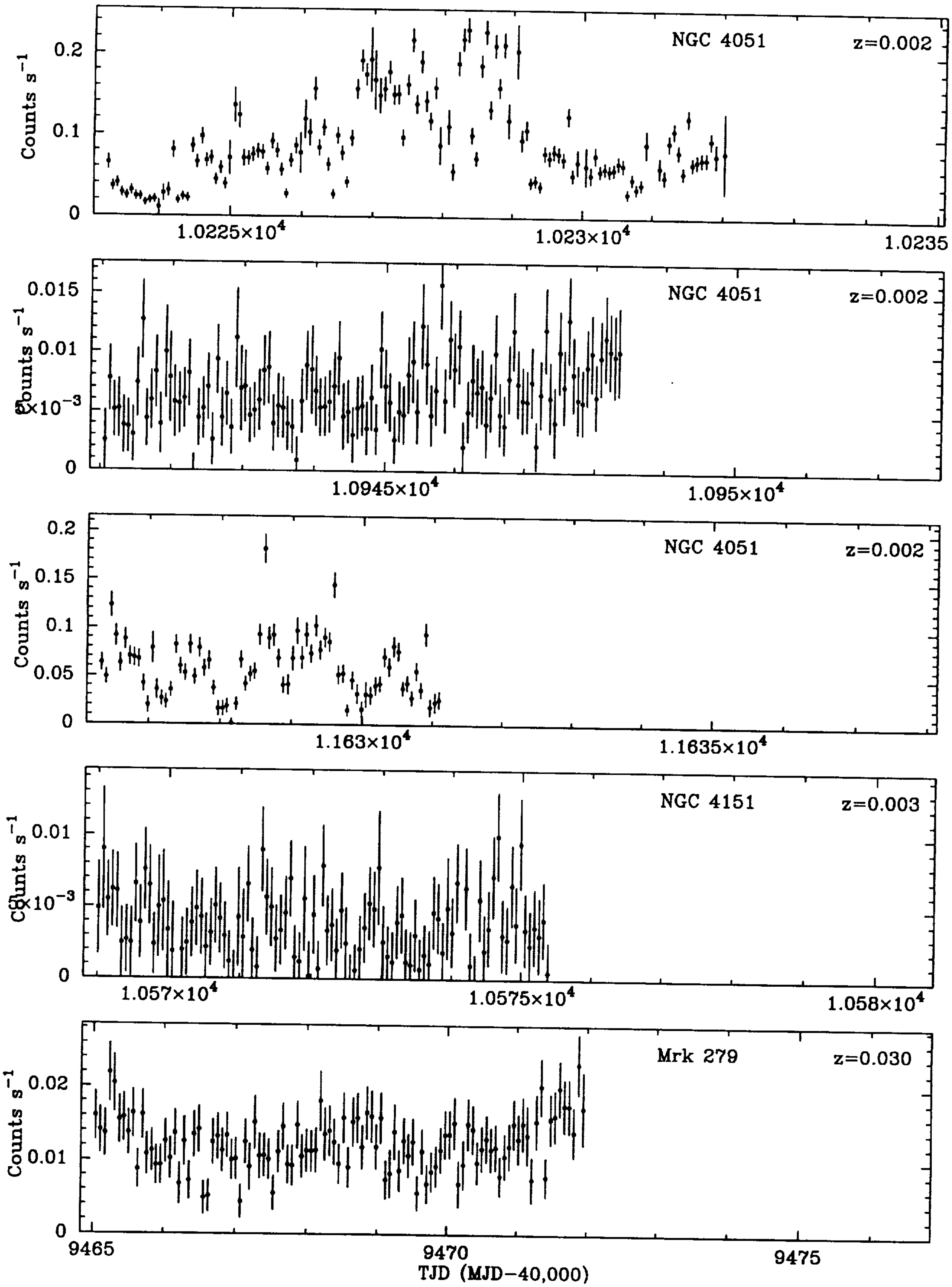


Fig. 1.— *EUVE* DS light curves of Seyfert galaxies. Each point represents one satellite orbit. Count rates are corrected for dead time and telemetry sharing.

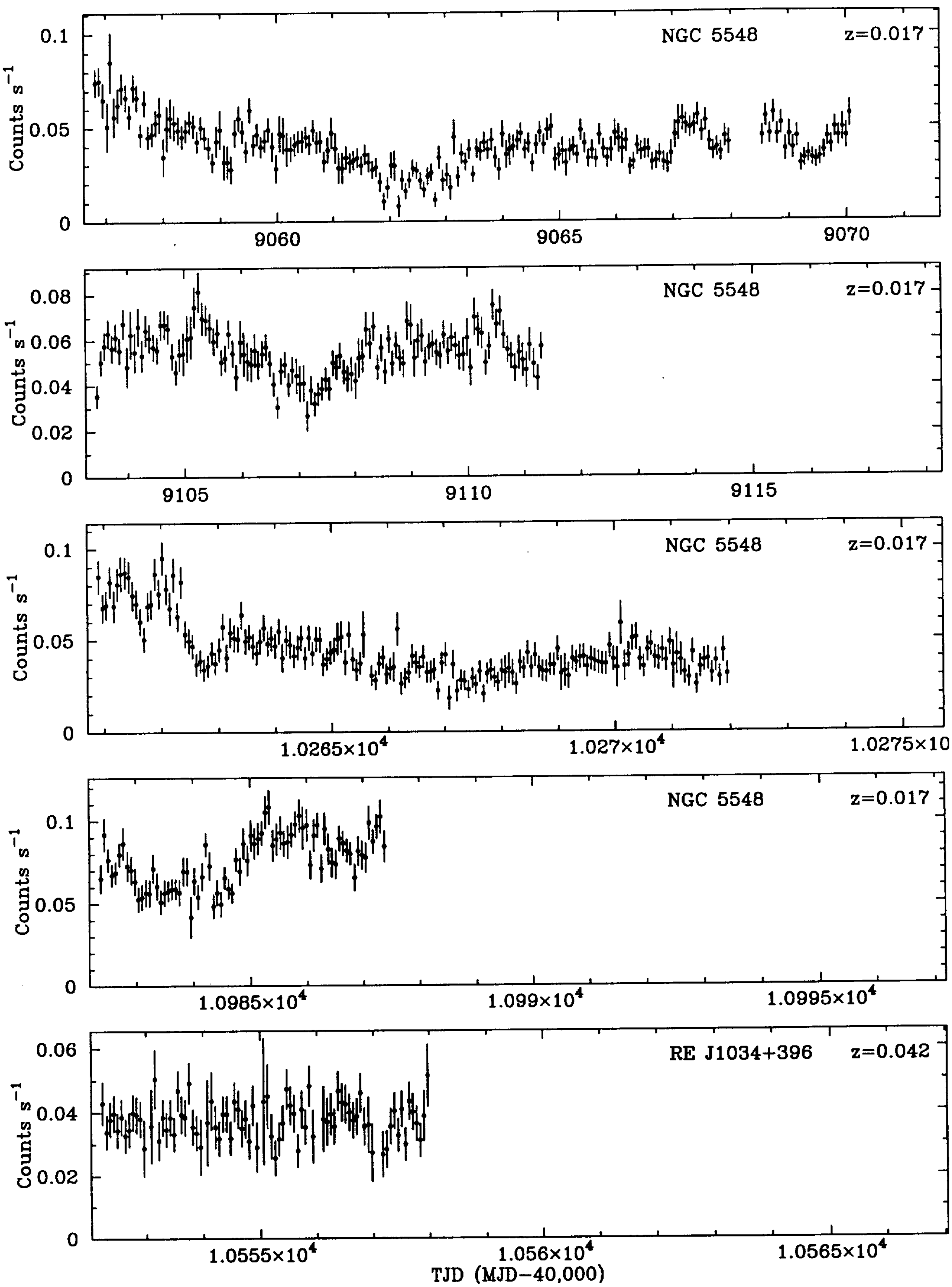
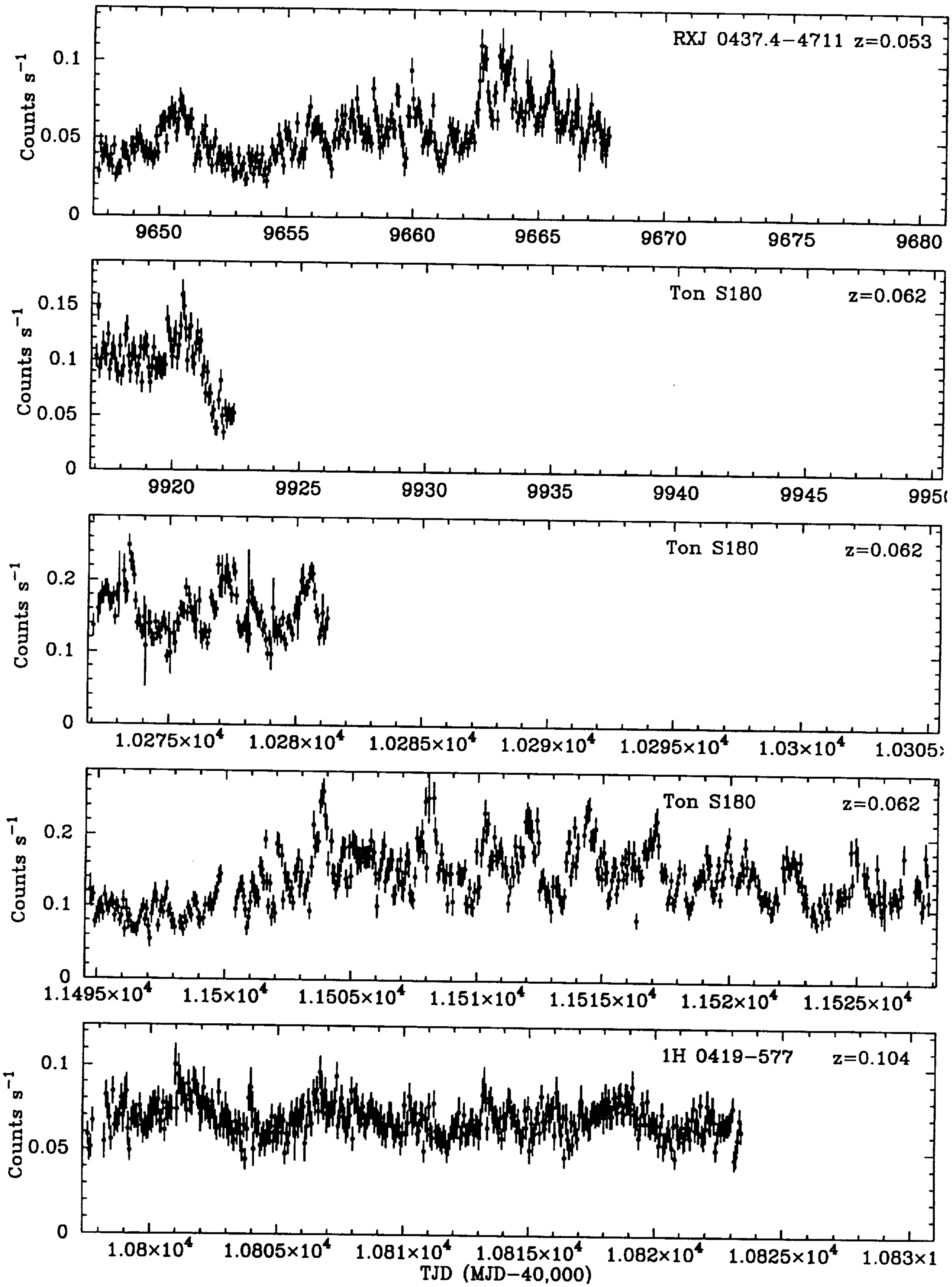


Fig. 2.— Same as Figure 1.



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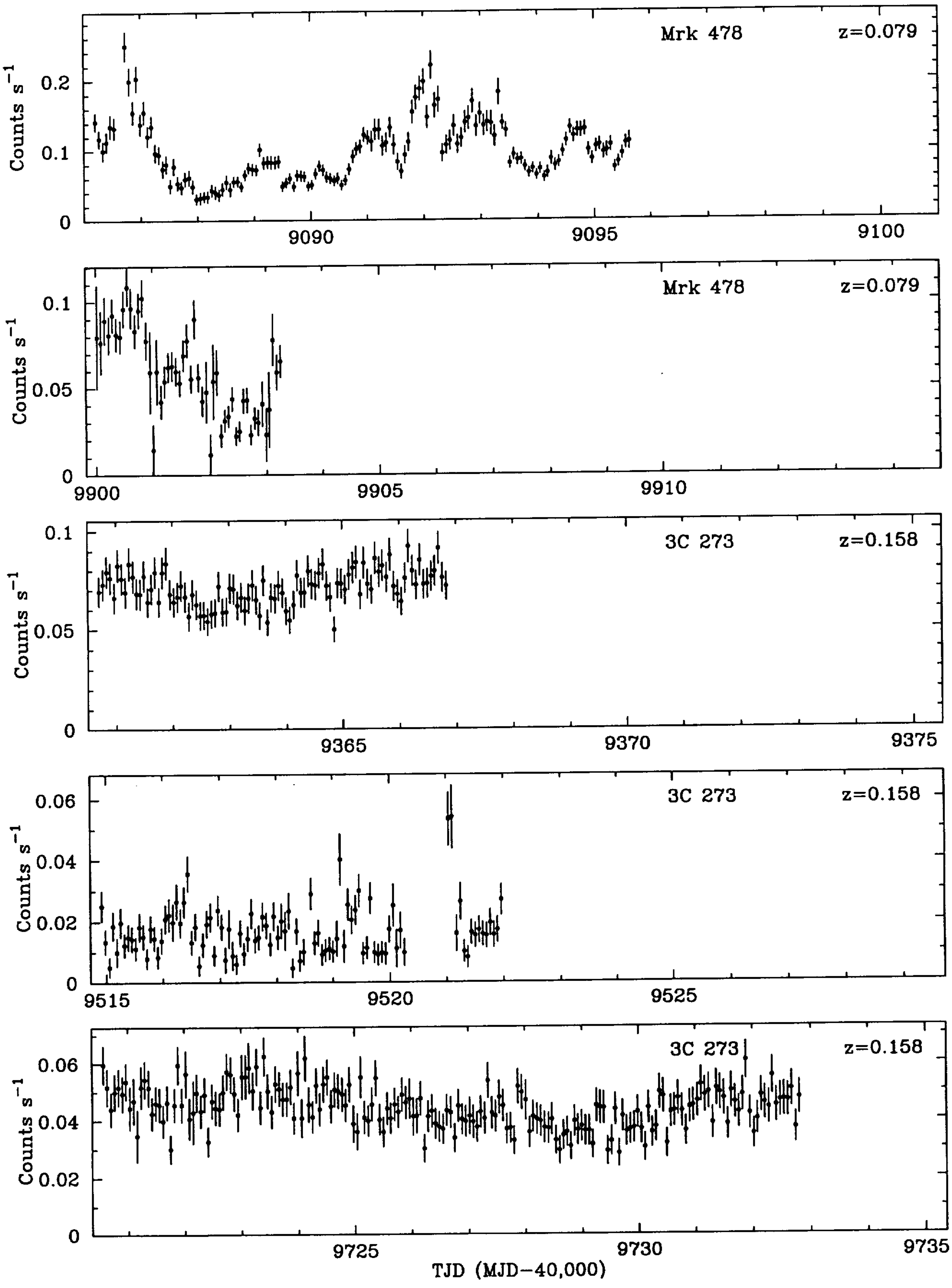

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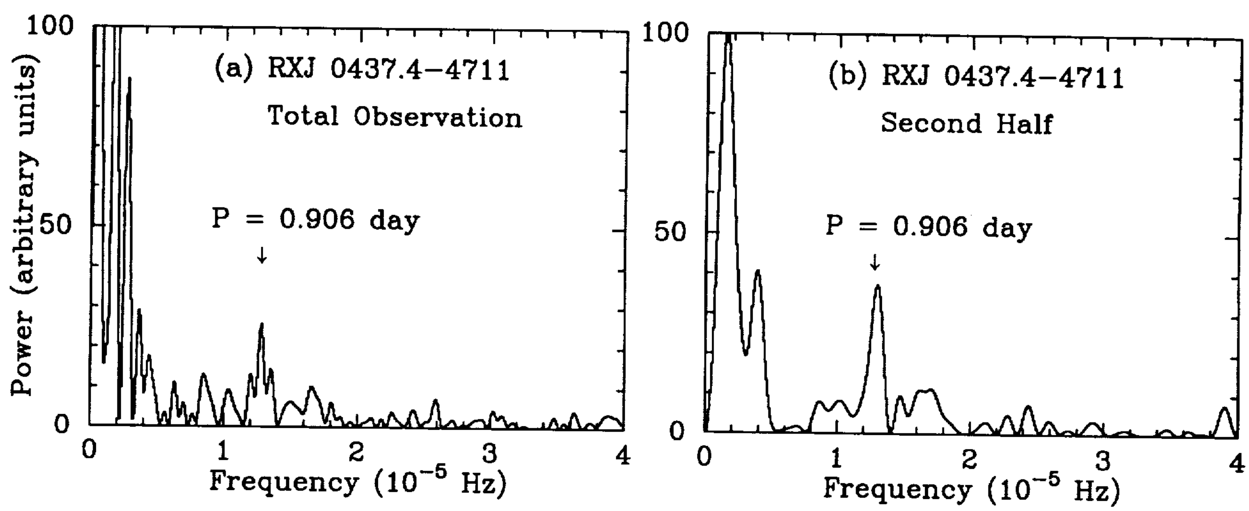

Fig. 5.— (*a*) Power spectrum of the entire DS light curve of RX J0437.4–4711, from Halpern & Marshall (1996a). A possible signal at 0.906 days is marked. (*b*) Power spectrum of the second half of the observation, showing enhanced significance of the 0.906 d signal.

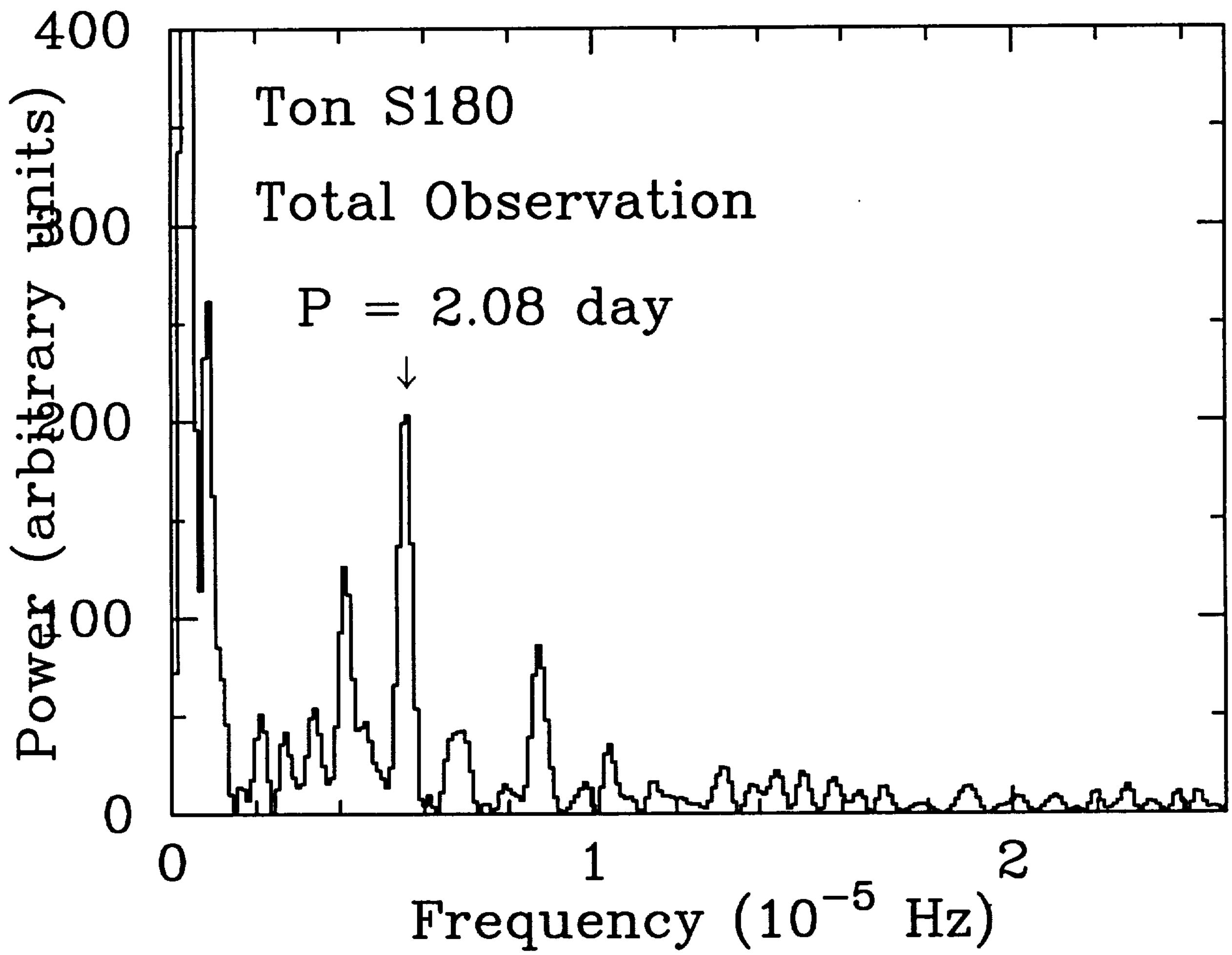

Fig. 6.— Power spectrum of the long *EUVE* DS light curve of Ton S180 in 1999 Nov–Dec.

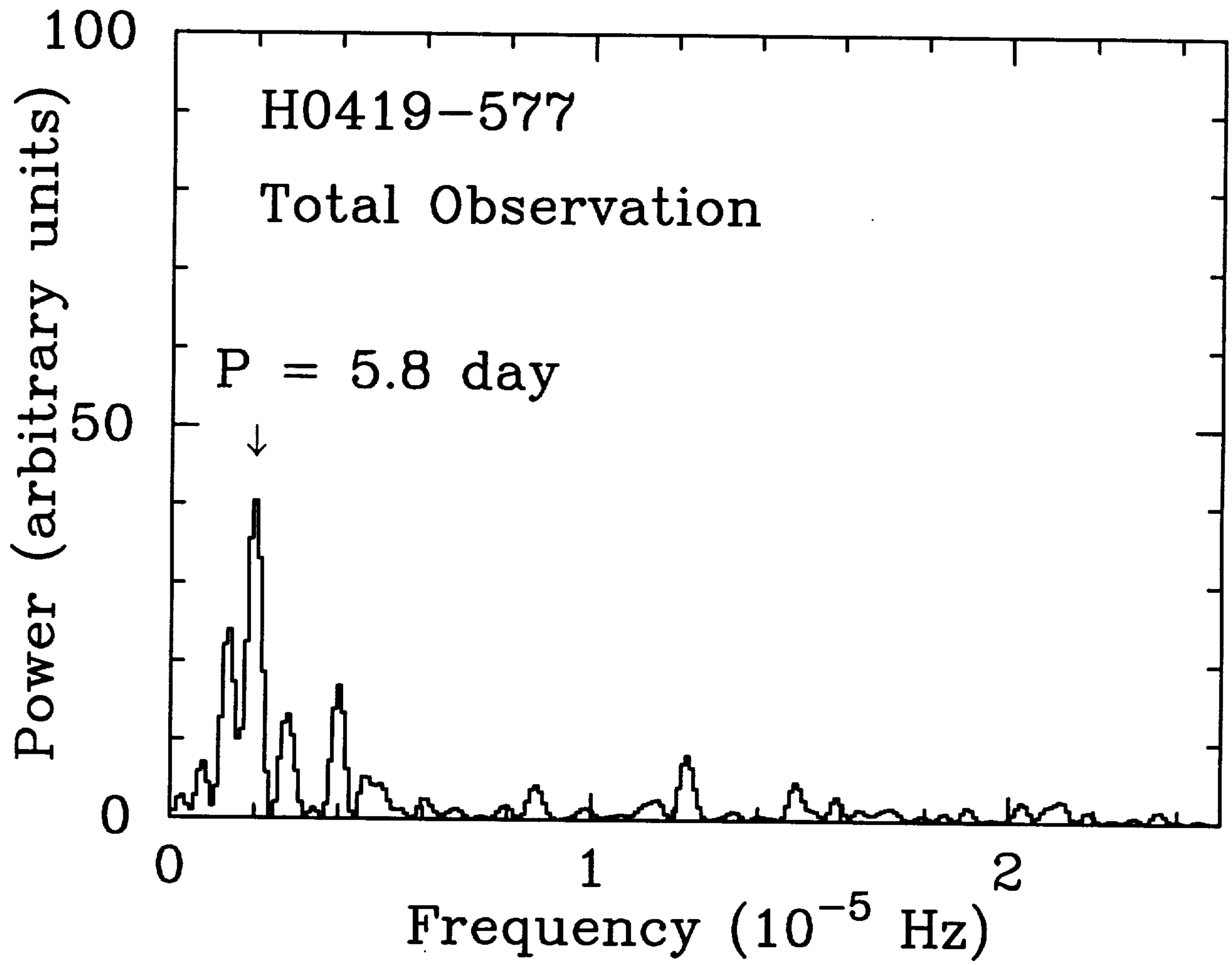

Fig. 7.— Power spectrum of the *EUVE* DS light curve of 1H 0419–577.

Table 1. Log of Observations

Object	Dates	MJD	Reference
NGC 4051	1996 May 20–29	50223–50232	1
NGC 4051	1998 May 8–15	50940–50948	2
NGC 4051	2000 March 23–28	51626–51631	
NGC 4151	1997 Apr 30 – May 7	50568–50575	
Mrk 279	1994 Apr 22 – Apr 29	49465–49471	3
RE J1034+396	1994 Apr 14–20	50547–50554	4
NGC 5548	1993 Mar 10–24	49056–49070	5,6
NGC 5548	1993 Apr 26 – May 4	49103–49111	5,6
NGC 5548	1996 Jun 26 – Jul 7	50260–50271	
NGC 5548	1998 Jun 18–23	50982–50987	7
Ton S180	1995 Jul 18–24	49916–49922	3
Ton S180	1996 Jul 8–17	50271–50281	
Ton S180	1999 Nov 12 – Dec 15	51494–51527	8,9
RX J0437.4–4711	1994 Oct 23 – Nov 12	49647–49667	10
1H 0419–577	1997 Dec 15 – 1998 Jan 10	50797–50823	11
Mrk 478	1993 Apr 9–18	49086–49095	3,12
Mrk 478	1995 Jul 2–5	49899–49903	
3C 273	1994 Jan 8–14	49360–49366	13
3C 273	1994 Jun 11–18	49514–49521	
3C 273	1995 Jan 3–15	49720–49732	13

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